CHAPTER 7

Safety Characteristics of Solid Propellants and Hazards of Solid Rocket Motors

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1. Introduction

The rapid growth of performance requirements and the new missions now performed necessitate:

- the use of increasingly larger rocket motors;
- the use of, and search for, increasingly powerful propellants, or propellants with increasingly faster combustion rates;

as well as finding propellants that remain very energetic while presenting a lower level of vulnerability.

Because of these trends, and of the evolution of safety regulations, it is now necessary to take safety issues into account at the beginning of any project.

2. Overview of Solid Propellant Rocket Motor Hazards

During the course of their entire life cycle, from production to utilization, solid propellant rocket motors can be found in many varied environments, and subjected to stresses corresponding to a series of various activities. Safety, under these conditions, is not only a function of the rocket motor *per se*, but of the environment in which the rocket motor finds itself.

During the life of the motor, various undesirable events are likely to occur:

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- propulsion caused by untimely ignition: untimely operation;
- inadvertent initiation, with thermal and mechanical effects:
  - explosion, with thermal, blast and projection effects;
  - detonation of the propellant grain, with blast and projection effects;
- faulty performance, that may also result in the undesirable events listed above.

These events are linked to the energy stored inside the propellant, and cause the following physical effects:

- thermal fluxes;
- active or inert projections, which can be characterized in terms of density, kinetic energy, and caloric energy:
  - propulsion,
  - projection of inert materials (fragments),
  - projection of energetic materials (propellants);
- blast, accompanying:
  - the mechanical explosion,
  - the detonation of a portion of the motor or the entire motor.

These are the primary threats from the solid propellant rocket motors; but, beyond these primary hazards, any active projection may lead to a secondary hazard (other than kinetic or calorific) caused by the impact of energetic material against walls or other objects against a wall.

In the case of a violent event, the blast causes an overpressure in the surroundings, which may remain modest in the case of an explosion (several kPa), or become very important (several MPa) in the case of a detonation.

3. Pyrotechnic Behavior of Solid Propellants

The pyrotechnic behavior of solid propellants can be characterized by:

- an evaluation of their various modes of decomposition;
- a knowledge of their reactions (threshold of reaction and type of reaction) when exposed to certain types of stimuli.

A full knowledge of the solid propellant behavior is very valuable because it allows us to:

- identify the modes of decomposition;
- know the level of stimuli that will cause a pyrotechnic reaction;
- compare the solid propellants with each other, and assess the general behavior of a solid propellant grain or of a rocket motor by comparing it against a reference solid propellant grain or rocket motor for which the behavior is well known, and based, in particular, on past experience.

3.1. DECOMPOSITION MODES OF SOLID PROPELLANTS

Propellants may, like any other explosive substance, exhibit various modes of decomposition.

3.1.1. Definition of the modes of decomposition

The major modes of decomposition are as follows:

- conductive combustion;
- convective combustion;
- detonation;
- thermal explosion.

Let us examine the propagation of decomposition into a solid propellant (Fig. 1). The "reaction zone" is the zone existing at any time between zone I — the propellant in its initial physical state, and zone II — the products of the decomposition.

- When the reaction zone travels inside the initial matter (zone I), through thermal conduction, we say that there is "deflagration."

In that case, volume, pressure, temperature and material velocity vary in a continuous manner from zone I to zone II inside of the reaction zone. The propagation velocity is lower than the sound velocity in the solid propellant and is called "deflagration velocity" (often called "the burning rate" of the propellant). Solid propellants deflagrate in a linear "cigarette burning" mode with slow propagation velocities up to high pressures.

- This steady propagation of the deflagration front into the unreacted solid propellant is often called conductive combustion. The propagation

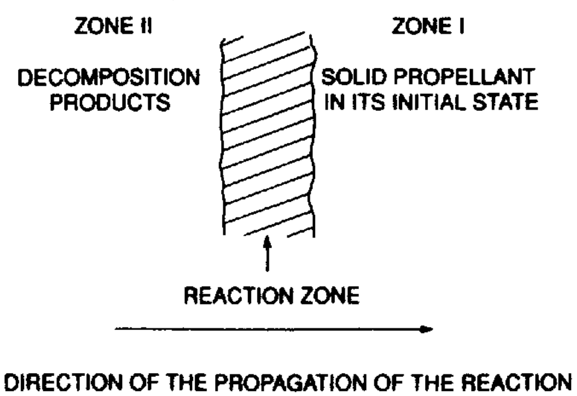


FIG. 7.1. Sketch of the propagation of the decomposition in a solid propellant.

velocities (burn rates) are in the range of several to tens of centimeters per second.

- When the reaction zone travels through the unreacted propellant (zone I) via a shock wave, we say that there is "detonation."

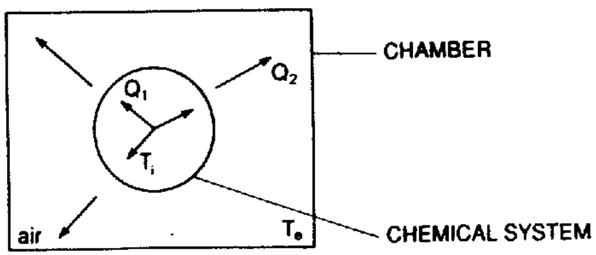
Across this detonation wave, the volume, the pressure and the material velocity of the matter experience a discontinuity. The typical propagation velocity of a detonation ranges between 2000 and 9000 m/s. The detonation is the functional decomposition mode of explosives. It is one of the accidental and feared decomposition modes for propellants.

- The term "convective combustion" is often used in the case of porous materials (a gunpowder layer, for example). In this case the reaction zone travels via the penetration of heated gases in the spaces existing between the grains. The propagation rates are in the 100–1000 cm/s range, and because of the increased burning area and subsequent compaction of the porous bed and accelerating pressure can lead to a deflagration to detonation transition (DDT).
- The thermal explosion (cook-off), as described by Frank Kamenetski [2], is a violent and somewhat peculiar reaction: it indicates a chemical decomposition in the core of the matter.

Let us consider a chemical system, likely to react to thermal stress, which is placed in a heated chamber at constant temperature T_e (Fig. 2).

There may be a critical temperature T_m such that:

- if $T_e \leq T_m$: then the heat produced per unit of time is lower or equal to the heat dissipated: $Q_1 \leq Q_2$. In this instance the state is steady and there is no self-heating inside the system;
- if $T_e > T_m$: then the heat produced is greater than the heat dissipated per unit of time: $Q_1 > Q_2$. Here the condition is unsteady. Because the heat



Where T_i = Initial temperature of system, such as $T_i << T_e$
Q_1 = Heat resulting from the reaction per unit of time inside the system
Q_2 = Heat dissipated by the system per unit of time toward the outside.

FIG. 7.2. Sketch of a chemical system subjected to constant thermal stimuli T_e.

produced cannot escape, the substance self-heats and can ignite, explode and eventually even detonate.

The closer the temperature T_e is to T_m, the greater the likelihood for the reaction to occur within the bulk of the propellant. It is in the vicinity of T_m that the "thermal explosion" phenomenon occurs.

3.1.2. *Main characteristics of solid propellant decomposition*

3.1.2.1. *Combustion*

Conductive combustion occurs, in solid propellants, in a very broad range of pressures (1 Pa to 1000 MPa). Studies have particularly concentrated on operational pressures, i.e. of the order of several MPa. Safety studies, however, are also interested in the other pressures regimes ("ambient" pressure and high pressures). The major methods used to characterize the combustion of propellants are as follows:

- determination of the regression rate, measured at atmospheric pressure on solid propellant grains;
- determination of burning rate versus pressure, using the classic "strand burner" method (a small amount of propellant in a large vessel to give essentially a constant-volume, constant-pressure burn. Each run determines the burn rate at a given pressure and many runs are required to give the burn rate pressure curve);
- combustion under high pressure that might represent situations of high level of confinement. This test is performed in a closed bomb with a static resistance to rupture in the area of 1000 MPa. (A larger amount of propellant is burned in the closed vessel giving a varied pressure-time history. Reduction of the pressure-time curve gives a range of burn rates versus pressure from one run.)

Figure 3 and Table 1 provide some samples of measurement results.

TABLE 1 *Burning rate versus the pressure range in mm/s*

Solid propellant type	Pressure			
	Atmospheric	7 MPa	100 MPa	400 MPa
Classic butalane*	1.6	10	/	/
Butalane, high burning rate	3 to 8	20 to 80	/	/
Butalane with HMX	1.5	13	108	356
Double-base	0.5 to 1	7	66	334
High energy	0.5 to 1.5	8 to 30	/	/

* Aluminized polybutadiène composite propellant.

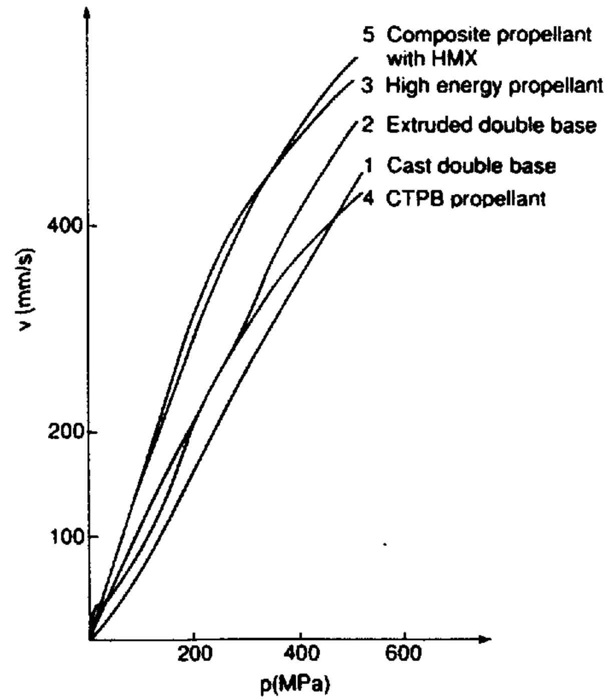


FIG. 7.3. Burning rate versus the pressure of typical propellants.

The monotonic character of these curves indicates that there is no abnormal burning (burning into cracks, or sample deconsolidation). In some instances, with certain high explosives, abnormal combustion occurs. This abnormal combustion may lead to convective combustion and in the extreme to deflagration to detonation transition.

3.1.[illegible]. *Detonation*

(a) Detonation in the classical sense of the term

T[illegible] main detonation properties of propellants are characterized by:

- [illegible] detonation critical diameter;
- [illegible] pressure required to initiate a given diameter of propellant often [illegible]asured by various gap tests;
- [illegible] TNT equivalency in terms of the blast effect.

D[illegible]nation critical diameter. The critical diameter is that diameter below wh[illegible] a steady-state detonation induced by a violent plane shock wave is no lon[illegible] able to propagate. That is, the shock wave "dies out." In explosives

this happens in a relatively sharp manner. For example if a cone of explosive is initiated at the base, the detonation will propagate toward the apex of the cone until the critical diameter is reached, at which point the detonation will die out. The stepped cylinder method (cylinders with decreasing diameter) is often used (see Fig. 4). In this test the diameter where the detonation stops is recorded by reading the witness lead plate. This diameter is called the detonation critical diameter.

Card gap test. This test consists of determining how many cards, made of cellulose acetate stacked to form a barrier, are necessary to prohibit the transmission of the detonation from the donor explosive (320 g) to the confined acceptor sample. The setup for this test is shown in Fig. 5.

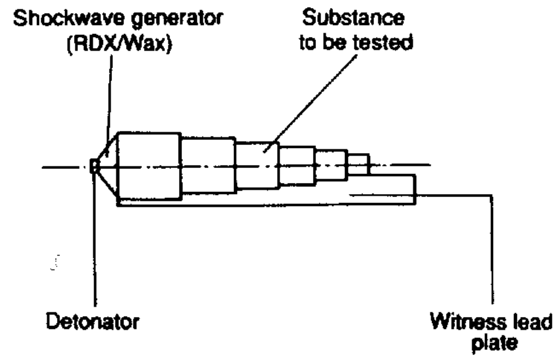


FIG. 7.4. Determination of the detonation critical diameter; SNPE test no. 10.

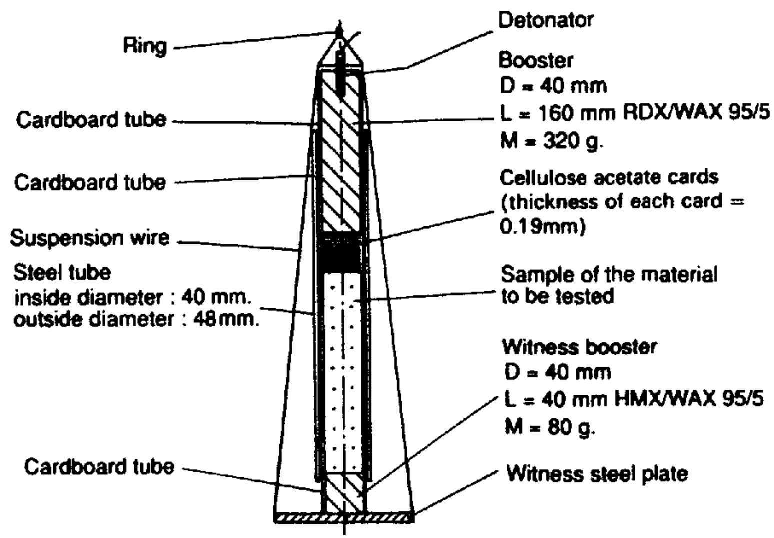


FIG. 7.5. French card gap test.

TABLE 2 *Detonic characteristics of solid propellants*

Propellant type	Critical diameter (mm)	CGT (number of cards)	TNT equivalency in blast effect
"Classic" composites	from 80 to 1000[a]	< 1	1.4
Butalane with HMX	from some mm to 100 mm[b]	from < 1 to 105[b]	1.4
Double-base	2 to 25	from 55 to 100	1.2
High energy	2 to 10	from 100 to 200	1.4 to 1.7

[a] Function of the solid loading ratio.
[b] Function of the ratio and quality of the HMX.

TNT equivalency in terms of the blast effect. This is the ratio of the TNT and propellant weight having the same effect at the same distances. Typical results are shown in Table 2.

We discover that the detonation characteristics of propellants are as varied as the formulas are different, but that the blast effect is about the same magnitude.

(b) New mechanisms for transition to detonation

We saw that the transition between deflagration and detonation caused by convective combustion cannot happen in an undamaged propellant grain with correct mechanical properties.

Nevertheless, several detonations occurred in the 1970s in the United States, during the development of the Trident missile [3-6]. It became necessary to explain these accidents, to imagine other mechanisms. Figure 6 presents, as a scheme, this new approach.

This scenario, which includes damage of the solid propellant leading to the creation of convective combustion conditions, reveals, on one hand, that correct design of the rocket motor is a key to operational safety, and on the other hand, that this DDT process can be eliminated by using propellant with a low propensity to fine fragmentation, therefore with good mechanical properties.

The most common test used to characterize the propensity of the propellant to this type of failure is the "friability or toughness" test, also known as the "shotgun" test. This consists of determining the condition of a piece of propellant grain fragmented through impact against a plane wall, by burning it in a closed bomb. The test principle is illustrated in Fig. 7.

The derivatives of the maximum pressure obtained on fragments of propellant grains, after impact, are recorded for each manometric chamber

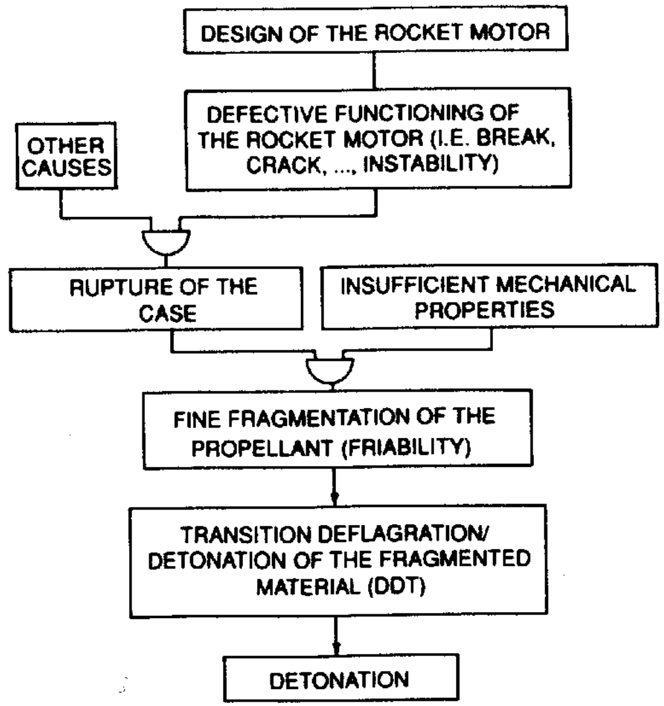


FIG. 7.6. Scenario of the DDT transition of a propellant grain.

test. These tests permit to plot the curve:

$$\left(\frac{dp}{dt}\right)_{max} = f(\text{impact velocity})$$

This curve is useful because ancillary experiments showed that when the propellant was damaged sufficiently to give 18 MPa/ms in the 90 cm^3 closed bomb, it was sufficiently damaged to produce DDT in a DDT tube experiment. Thus the impact velocity that causes damage sufficient to produce this 18 MPa/ms dp/dt in the 90 cm^3 closed bomb, is called the critical impact velocity or CIV. Values of CIV of 200 m/s are considered good, that is a tough propellant which is not very friable, while 100 m/s is indicative of poor, friable propellant.

These accidents have led to the analysis of the failure mode of the firing operation. The experiments carried out revealed, in particular, the so-called "XDT" phenomenon (delayed detonation through shock). J. F. Kincaid [7] has put together a study combining all of these tests and their results.

The delayed detonation occurs at a time later than the normal transit time of the shock through the material. These reactions not only occur at times

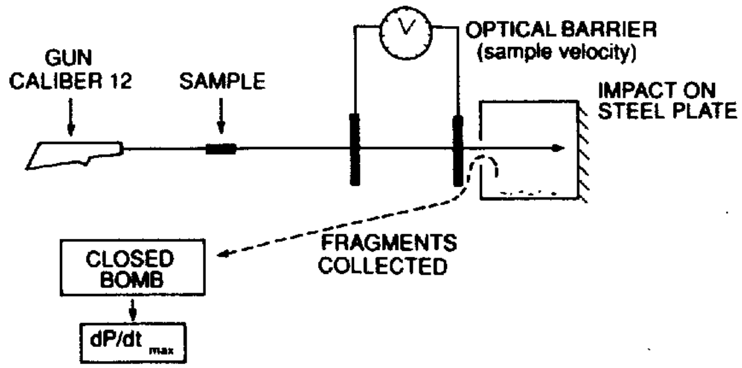


FIG. 7.7. Resistance to dangerous fragmentation.

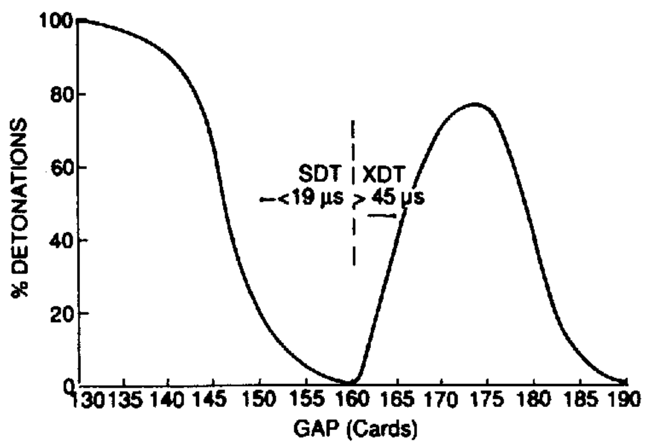


FIG. 7.8. NOL card gap test results showing SDT and XDT (from ref. [8]).

longer than characteristic of SDT, they also require a lower stimulus, for example an increased number of cards in the card gap test as shown in Fig. 8.

Sample size and mechanical properties also determine the initiation threshold as seen in Fig. 9.

So, detonation initiation by shock can be resumed in the following manner:

- high shock → SDT 1 D initiation;
- low shock → XDT 2 D and 3 D initiations.

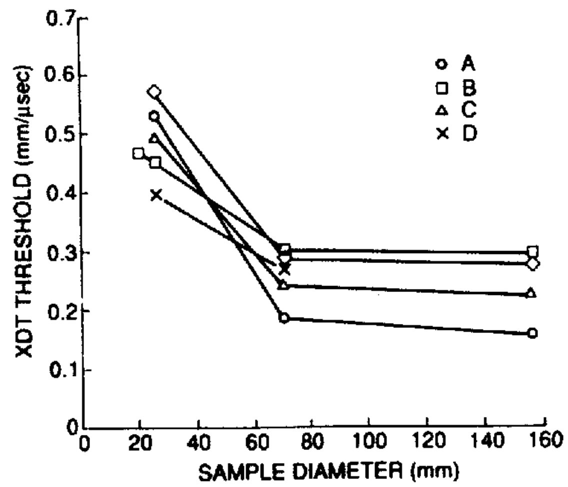


FIG. 7.9. Dependence of the velocity threshold for observation of XDT on sample diameter for various propellants A through E (from ref. [9]).

3.2. SENSITIVITY OF PROPELLANTS TO VARIOUS STIMULI

3.2.1. *Impact sensitivity*

Traditionally, at SNPE the Julius Peters drop-hammer test was used to determine the sensitivity to impact of high explosives. Initially, it was also used for solid propellants. Its major drawback is the very small quantity of

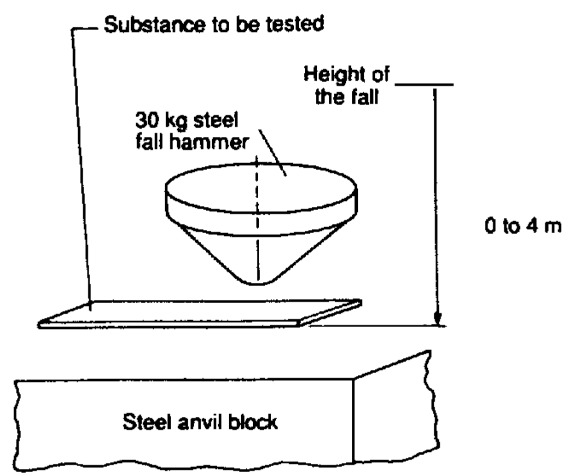


FIG. 7.10. Sensitivity test with a 30 kg fall-hammer; SNPE test no. 17.

material that is used to perform the test: 20 mm^3. The "30 kg fall-hammer test" is now preferred; its major advantage resides in the capability of testing 100 g of material.

This test is, in addition, very interesting because it allows us to make a distinction between the types of reaction of the explosive substance:

- violent reaction with propagation (detonation);
- local reaction or ignition.

Generally, there is no propagation of violent reaction in the specimen of any solid propellants, up to an impact stimulus from 4 m high. However, local reactions, ignitions with or without propagation are observed.

3.2.2. *Sensitivity to friction*

As for the impact sensitivity testing discussed above, the sensitivity to friction test is carried out with the Julius Peters testing device. The principle of this device is illustrated in Fig. 11. It allows classification of the friction sensitivity of the solid propellants, but the safety margin in relation to the stimuli cannot be determined. Typical results obtained are given in Table 3.

To determine the safety margin of an operation performed on the solid propellant, this test can be complemented by other selective tests. These consist of rubbing propellant specimens, weighing several grams on surfaces

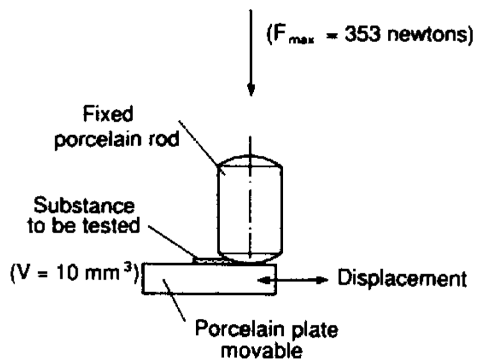


FIG. 7.11. Device for the friction sensitivity test "Julius Peters"—SNPE test no. 16.

TABLE 3 *Sensitivity to friction of solid propellants*

Composite	80 to 150 N
Composite with burning rate modifier	50 to 90 N
Double-base and high energy without ammonium perchlorate	50 to 353 N
Ammonium perchlorate high energy	60 to 150 N

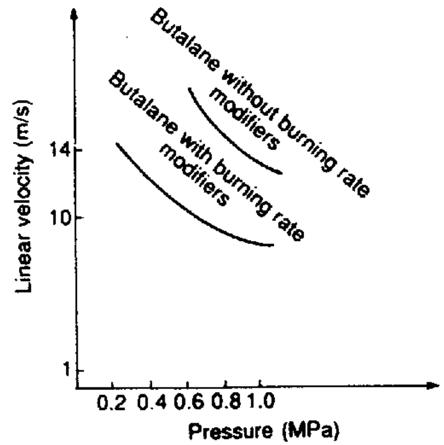


FIG. 7.12. Results of linear friction tests; SNPE test no. 76.

selected according to the data required, for periods of time lasting eventually up to several tens of seconds. By performing a series of tests a curve can be plotted from which safety margins can be obtained for pyrotechnic events considered as likely to occur during an operation inducing this type of stress. Figures 12 and 13 provide examples of such curves.

The solid propellant itself can be a surface that is selected, in which case an increase in sensitivity was noticed when moving from a steel surface to a propellant surface.

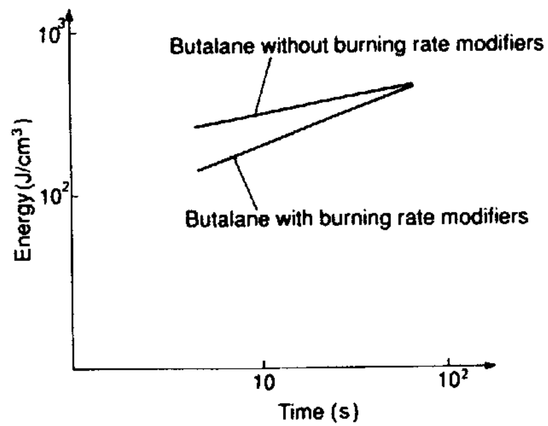


FIG. 7.13. Results of rotary friction.

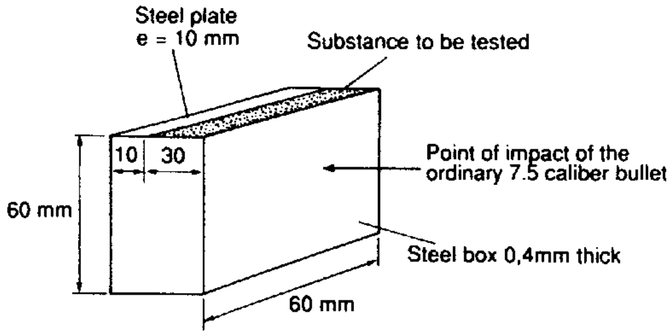


FIG. 7.14. Sensitivity to 7.5 mm caliber bullet impact; SNPE test no. 32.

3.2.3. *Sensitivity to projectiles and fragments*

It is, in fact, the sensitivity to impact from bullets that is usually determined. A test currently performed is shown in Fig. 14.

Generally, the results obtained at ambient temperature are as follows:

- ignition in all solid propellants;
- no violent reaction up to impact velocity of 930 m/s.

This systematic ignition, which we see in all composite propellants regardless of the velocity (beginning at 385 m/s), occurs in double-base propellants beginning at 555 m/s.

In Nitrargols the ignition threshold velocity decreases when the ammonium perchlorate content increases. These results have been confirmed by tests performed with rocket motors.

Nevertheless for rocket motors using solid propellant with small critical diameter of detonation we have to perform tests on more realistic models. In fact it is necessary to take into account that the vulnerability of a rocket motor is the vulnerability of a system. Some new results show that detonation can be obtained essentially due to a bore effect [10].

In this work detonation occurred when the bullet passed through the center bore in the motor, while detonation did not occur when the same caliber bullet with the same velocity passed through just propellant web (impact off-center so that the path of the projectile does not pass through the bore).

3.2.4. *Sensitivity to temperature increase*

3.2.4.1. *Temperature of ignition*

The ignition temperature of a solid propellant is the temperature at which ignition of the solid propellant occurs when the temperature of a small-size

specimen is raised; it is dependent only on the composition when the weight, the shape and other aspects of the specimen are given.

This characteristic varies with the temperature gradient. Two tests are commonly performed using 200 mg of shredded product:

- progressive heating with a standard gradient of 5°C/min;
- Sudden heating, which is achieved by plunging the product suddenly into an environment at a specific temperature. The ignition temperature is the temperature at which the propellant ignites within 5 s.

3.2.4.2. *Temperature of thermoinitiation of an unconfined solid specimen*

In the preceding sections we gave a brief description of the thermal explosion phenomenon. This phenomenon is different from that of ignition.

A composite propellant with ammonium perchlorate that does not contain any burning rate modifier, for example, can react very violently at a temperature of 175°C after several hours. This is the case of an accelerated chemical reaction at the core of the sample. A summary of the situation is given in Fig. 15.

The sensitivity to thermal explosion is determined through the cook-off test. The principle of this test is given in Fig. 16.

The specimen is contained in a cylinder made of steel or aluminum. The results of this test can be influenced by the environment and the size of the specimen [11]. The results obtained from progressive heating and thermoinitiation tests are indicated in Table 4.

Whenever we have seen the thermal explosion phenomenon occur, it always is within a narrow range of temperatures (approximately 10°C).

Nitrargols G containing ammonium perchlorate have no temperature

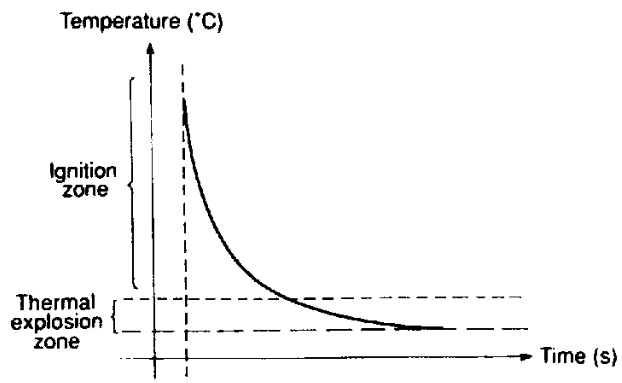


FIG. 7.15. Diagram of the evolution of the reaction temperature versus time.

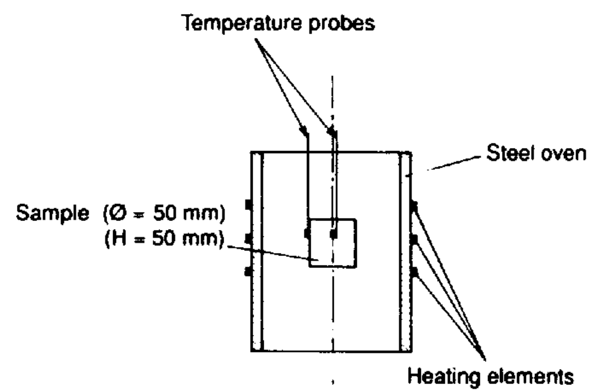


FIG. 7.16. Principle of the cook-off test.

TABLE 4 *Experimental results from thermal stimuli*

Propellants	Ignition temperature (progressive heating)	Results: Cook-off – Ø 50 mm, *h* 50 mm (at constant temperature) — Result	Maximum pyrotechnic event
"Classic" composites	270 to 320	Approx. 175°C	Thermal explosion
High burning rate composites	280 to 170	Decreases until 120°C when the catalyst ratio increases	Same
Epictète (CDB)	165 to 185	100 – 110°C	Same
Nitrargols (high-energy propellant)			
without perchlorate	160 to 180	110 – 110°C	Same
with perchlorate	170 to 180	No critical values	Ignition

limits or cook-off phenomenon. Decomposition occurs through burning. Test results that are now available demonstrate that their decomposition is directly controlled by the consumption of the nitric ester stabilizers of the formulation. The reaction temperature is independent of the size of the specimen.

3.2.4.3. *Fast cook-off and slow cook-off*

These terms describe thermal stimuli observed, typically, in munitions in an operating environment.

- Fast cook-off corresponds to a munition exposed to an intense and direct fire. The munition is engulfed within the flames.
- Slow cook-off corresponds to a munition subjected to a relatively low heat flux. Under these conditions it is understandable that the temperature of the munition increases very slowly.

The tests discussed in Sections 3.2.4.1. and 3.2.4.2. can also be used to study this type of slower thermal stimulus.

3.2.5. Sensitivity to static electricity

3.2.5.1. *Background*

Until 1975, France, like most other countries, performed a test using around 100 mg of propellant to determine its electrostatic sensitivity. This test is comparable to the Picatinny Arsenal test [12] and is shown in Fig. 17. In this test, propellants in the shape of compact discs were always found insensitive. Occasionally, after some tests, the propellant discs were found to have a very small axial hole.

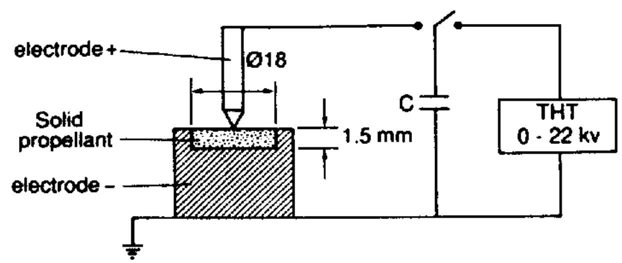


FIG. 7.17. Sketch of initiation by electrical spark.

3.2.5.2. *Recommended operational method for the tests*

During the 1970s, ignitions of composite propellant grains occurred in manufacturing facilities. Investigations demonstrated that these ignitions could only have been caused by static electricity.

Additional tests were then performed, leading to the adoption of a new testing method that proved to be more representative of the accidents that had occurred [13]. The principle of this new method is shown in Fig. 18.

Using a pointed electrode, the propellant grain (Ø = 90 mm, height = 100 mm) is subjected to the discharge measuring 34.7 nF, charged at 30 kV. Thirty successive discharges are released into the grain. The result is considered as negative when there are no cracks and no ignition. A composition is declared electrostatic-insensitive when negative results have

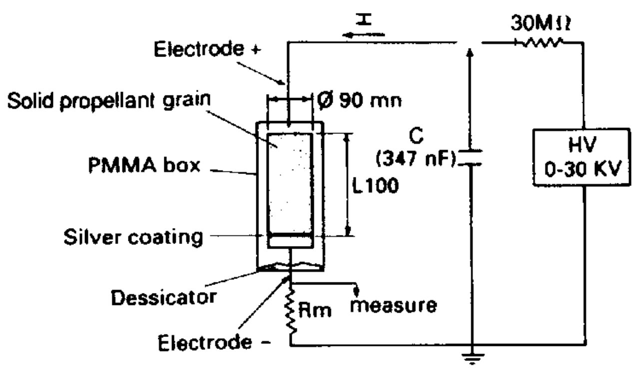


FIG. 7.18. Sketch of the testing setup for electrostatic.

been obtained on three grains of that propellant composition, at the specific temperature. Further details can be found in the chapter on composite propellants (Chapter 10).

4. Assessment of the Risks Presented by Propellant Grains

A risk assessment consists of assigning a probability of occurrence to each potential hazard, for each phase of the life of propellant grain. There are two traditional methods used:

- the regulatory approach;
- the analytical study.

4.1. THE REGULATORY APPROACH

4.1.1. Major regulations

The propellant industry is subject to the application of various regulations. The most general in its scope of these regulations is the UN Recommendation [15].

Generally speaking, these regulations establish hazard categories or sections for the various explosive substances, solid propellants in this case, corresponding for the most part to the pyrotechnic effects likely to be encountered.

Table 5 provides, for example, the definitions of the hazards divisions of the French Labor Regulation (almost the same definition as UN).

They also provide data for a decision chart, based on tests or experiments whose results have been quantified and compared with criteria or sanctions

TABLE 5 *Classification of hazards of explosive substances and objects*

Class number	Division number	Characteristics of the substances or articles in this section
1		
	1	Substances or articles essentially involving a mass explosion hazard, i.e. affecting almost the entire load virtually instantaneously.
	2	Substances or articles involving a projection hazard but no mass explosion hazard.
	3	Substances or articles involving a fire hazard with a minor blast or projection hazard, and no mass explosion hazard. This division includes the following two subdivisions: Subdivision 3a, consisting of substances or articles whose combustion gives rise to considerable radiant heat; Subdivision 3b, consisting of substances or articles that burn fairly slowly, or burning one after the other with minor blast and projection effects.
	4	Substances or articles involving no significant hazard, designed or packed so as to exhibit only relatively minor hazard or whose effects, in case of ignition or initiation, do not give rise to the projection of fragments of appreciable size, and remain in any case small enough not to significantly hinder fire-fighting operations and the application of emergency measures.
	5	Substances that are, when they explode, as hazardous as those of Section 1, but that are relatively insensitive. These substances display a very low probability of initiation and transition from combustion to detonation except when in large amounts in a small and confined space. They may not explode when exposed to outside fire.

allowing the classification of the product into one or another of the hazards divisions defined in Table 5.

Finally, they provide a general definition of the dispositions, precautions and facility designs for the established classes of products.

National or international regulations on transport, storage, possession, and use of hazardous substances are being or have been revised in accordance with the UN recommendations.

The differences existing between the procedures are explained by the fact that these regulations take implicitly into account the probability of the occurrence of a stimulus. It is therefore understandable, for instance, that stimuli considered in the case of storage are different from those in the case of transport.

The only regulation that explicitly considers the probability of the occurrence of pyrotechnic events is the French Labor Regulation [16].

The test most widely used for all regulations is the card gap test. There are, however, various versions of this test, and the criteria followed by the various regulations differ, possibly resulting in making comparisons difficult. The test used in France and related results are described in Section 2. The determination of whether a product should be upgraded from Hazard Division 1.3 to 1.1 is based on card gap tests greater than 240 French cards in France and 70 American cards in the United States, the latter being equivalent to approximately 95 French cards, because the thickness of the cards is different. The positions on this criterion seem to be very far apart. It would be necessary, however, in order to judge the validity of either regulation, to compare them in their entirety and not on that particular point only.

4.1.2. Labor regulations

The assessment of threats and the corresponding assignment to a hazard class in accordance to French labor regulations is particularly applicable to small propellant grains rather than large grains for various reasons, including the significant number of specimens required (i.e. cost and space limitations). The assignment to a hazard class is done based on a procedure which includes a series of tests, and is applied to new explosive substances or articles (such as free-standing grains, rocket motors, and others).

The procedure involves five steps:

The first step involved in this classification consists of determining whether the rocket motor or the propellant grain is a new type or "insufficiently known".

Of course, when the design of the rocket motor, or the propellant grains, shapes or compositions, is in fact very new, it is *ipso facto* insufficiently known. But this case is a very rare one, and what is termed as new is the result, in practice, of more or less extensive modifications to existing, known propellant grains.

In practice, to be able to avoid having to perform all required tests, it is necessary to provide proofs that a new propellant or motor can be placed in the same category as existing propellants or motors.

These studies and analyses, which make up the first step of the procedure, can be summarized as follows:

- acquire the technical elements of the definition of the type of propellant grain or motor under consideration;
- identify the differences;
- analyze these differences;
- conclude whether the analogy is reasonable — if it is not, proceed to the second step.

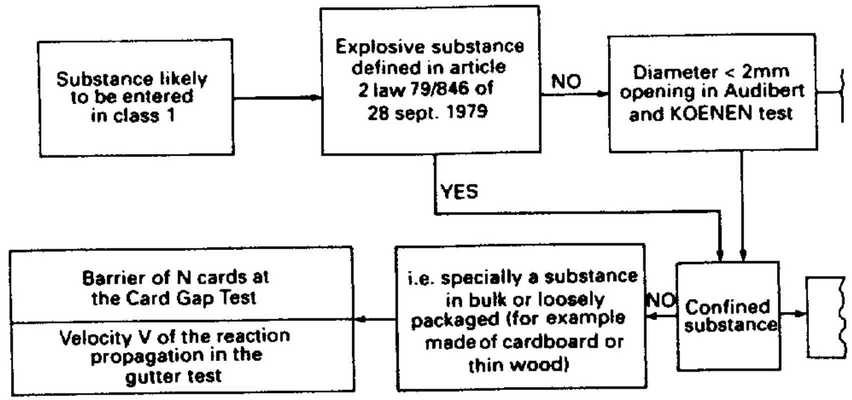


FIG. 7.19. Procedure to include propellant grains in hazards divisions—right part of the decision flow-chart.

When in doubt, the higher hazard class is selected, as described above. Tailoring of the procedure to the case of propellant grains is discussed below. The beginning of the path is shown by the thicker line in Fig. 19, within a general decision flow-chart.

The second difficulty involved in the classification, based on the flow-chart, is coming to a conclusion about the meaning of the word "confinement." Consequently, the second step consists of qualifying the confinement of a propellant grain.

One possible method is:

The "decision chart" indicates that the substances in bulk, or loosely packed (i.e. in a cardboard box, or a thin wood box) are considered to be "not confined," or "in an object that provides no confinement".

This confinement concept aims essentially at ensuring that the risks of transition from deflagration to detonation are taken into account. Furthermore, we know that a propellant will not transit to detonation unless it has been previously finely fragmented after, for example, an early-damaged material.

As long as the constituent material of the grain is undamaged and solid, the propellant grain itself becomes in some ways like an open container. We are able, then, to consider that the confinement is tied only to the Klemmung of the propellant grain and to the probable effects of the bursting of the motor, whether it acts as a container under pressure or it is case-confined in the case of accidental burning. A technical equivalence of the confinement concept may then be suggested for the rocket motor.

The technical equivalence of the definition for the expected confinement is specific to the particular object that a solid propellant motor constitutes.

When the four following conditions are satisfied simultaneously, it is said that there is no confinement.

- *First condition.* This concerns the propellant constituting the solid propellant grain.
  This propellant must burn in a normal layerwise manner up to very high pressure levels.
- *Second condition.* This requirement is related to the violence of the eventual bursting of the container under pressure, which is the propellant grain itself in the case of accidental burning.
  Precise specifications related to the characteristics of the propellant and its case are used to determine these two conditions.
- *Third condition.* The propellant grain is loosely packaged, or not at all (absence of confinement from packaging).
- *Fourth condition.* The storage condition of a number of rocket motors does not create any significant additional confinement (absence of confinement in storage).

When all four conditions are satisfied we may say that there is no confinement and the left portion of the decision chart is used. If even one of these conditions is not satisfied, the right side of the decision chart is used.

The following steps consist of characterizing the situation and following the applicable procedure for classification.

Finally, the fifth and last step consists of ensuring that the quality assurance of the program guarantees that each propellant grain or rocket motor will have the same characteristics of the specimens used to perform the classification tests.

4.2. ANALYTICAL ASSESSMENT

This method is much more general and complete than the preceding one [17]. It is better suited for large rocket motors.

Three steps are involved:

The first step consists of preparing an exhaustive list of all possible stimuli. By stimuli, we mean both a stimulus proper, i.e. coming from the outside, and possible failures of the system, in particular, a defective operation. The list created must show, for each stimulus:

- the probability of the stimulus;
- the gravity of the stimulus (such as among other things, intensity and duration).

The second step consists of creating a general scenario of the behavior of the rocket motors under the various stimuli identified in the first step. A typical scenario is shown in Fig. 20. The goal of this type of scenario is to assess the

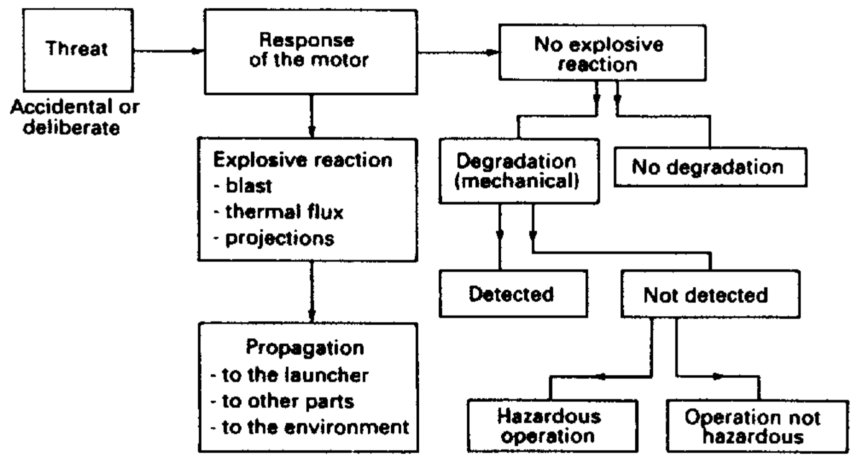


Fig. 7.20. General scenario of the behavior of a rocket motor faced with a threat.

explosive hazards and to discover eventual degradations and their consequences.

The third step involves the analysis of the possible behavior of the rocket motor for a specific stimulus. A sample of an analysis is given in Fig. 21, for the case of a threat resulting from a shaped charge.

The result of this analysis is the probability of an undesirable pyrotechnic event.

For the third step, the following are indispensable to be able to quantify the probability:

- the performance of basic tests;
- the use of computer codes;
- the performance of tests on models.

For instance, the example in Fig. 21 requires, among other things:

- knowledge of the critical detonation diameter of the composition, which is a basic test;
- determination of the fragmentation condition due to the stimuli, which requires the use of a code.

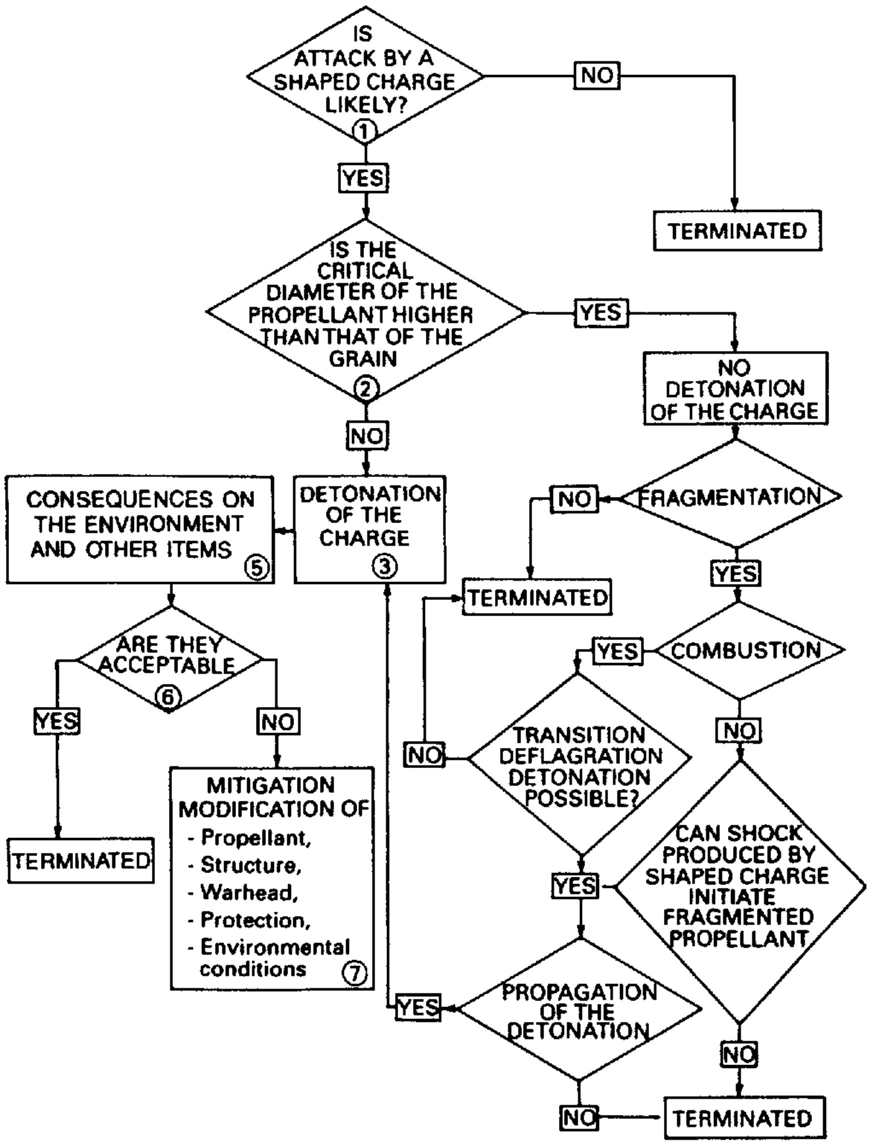


FIG. 7.21. Analysis of an attack by a shaped charge jet.

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